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Intraday Liquidity Around the World *

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Abstract

We study intraday liquidity usage and its determinants using a unique cross-country data set on large-value payments. We document that the amount of intraday liquidity that financial institutions around the world use *each day* equals, on average, 15% of their total daily payment values or 2.8% of their countries' GDP. We then define and calculate system-level measures of liquidity efficiency and inequality in liquidity provision. We show that these measures vary systematically with the degree of payment coordination among payment system participants, the quantity and opportunity cost of central bank reserves and institutional characteristics, such as incentives for early payment submission and liquidity saving mechanism (LSM) design. Our results are consistent with the notion that payment system participants behave strategically and manage intraday liquidity actively. Participants also appear to condition their payment behaviour on specific LSM characteristics, which may weaken some of the LSMs' intended effects.

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1 Introduction

Financial institutions manage their intraday liquidity to meet payment obligations that arise during the day. These are typically large payments that financial institutions make to one another, in central bank money, using dedicated electronic networks collectively referred to as large-value payment systems (LVPSs). LVPSs in most jurisdictions settle their participants' payments on a gross basis in real time, meaning that each payment needs to be fully pre-funded.[1] While settlement of transactions on a gross basis helps to reduce credit risk [Bech and Hobjin (2007), Kahn and Roberds (1998)] it is also liquidity-intensive with intraday liquidity needs arising whenever there are timing mismatches between same-day incoming and outgoing payments. These intraday liquidity needs can be sizeable and usually much larger than participants' net daily obligations, especially during times of stress. This became evident during the financial crisis of 2008-09 by the collapse of Lehman Brothers.[2] In response, regulatory reforms since then have sought to address risks arising from intraday liquidity shortfalls.[3]

This paper is the first to measure intraday liquidity usage across multiple jurisdictions over a long period of time and study its determinants. For this purpose, we gather proprietary data on individual LVPS transactions between financial institutions and other payment system participants. We use these data to describe overall payment activity and to measure, for each jurisdiction and on a daily frequency, the aggregate amount of liquidity that participants use to cover their intraday obligations. Our data span several major economies, which collectively account for more than 45% of the world's GDP and as such is highly representative of global payment activity and intraday liquidity usage. The jurisdictions in our sample vary with respect to institutional arrangements such as the terms under which the central bank provides intraday credit, the presence of incentives for participants to settle their payment obligations earlier in the day, as well as the presence and the particular design features of LSMs.[4] This allows us to compare and contrast the impact of these arrangements on intraday liquidity usage. Furthermore, our data spans an eventful 17-year period (2003-20) that includes the financial crisis of 2008-09 and the subsequent central bank interventions that took place in several of the jurisdictions of our sample.

We start our analysis by measuring, for each jurisdiction, the aggregate amounts of

[1] Such payment systems are referred to as Real-Time Gross Settlement (RTGS) systems.

[2] According to the examiner's post-mortem for Lehman, the company had a total liquid asset pool of $25 billion as of September 12, 2008. Of this, $16 billion was pledged as collateral with clearing and custodian banks with the exclusive purpose of covering intraday liquidity needs. This meant that a substantial fraction of Lehman's liquid assets were encumbered and unavailable to meet other obligations, which on that day exceeded Lehman's available liquidity and led to its demise. See Valukas (2010).

[3] Intraday liquidity risk is directly addressed by the "Principles for Sound Liquidity Risk Management and Supervision" issued by the Basel Committee on Banking Supervision (BCBS) [BIS (2008)]. For instance, Principle 8 states that "A bank should actively manage its intraday liquidity positions and risks to meet payment and settlement obligations on a timely basis under both normal and stressed conditions and thus contribute to the smooth functioning of payment and settlement systems". For an overview of intraday liquidity regulation see Ball et al. (2011). The BCBS has also published a set of tools for monitoring intraday liquidity, which internationally active banks are required to apply [BIS (2013)].

[4] LSMs are mechanisms that offset or net payments on a frequent basis during the day. As such, they allow payment system participants to economise on intraday liquidity. The exact payment offsetting/netting criteria may vary across LSMs. We provide more details on LSM design characteristics in Section 4.4.

liquidity used by participants to cover their payment obligations during the day. Participants can meet their obligations by either using their own reserve balances, obtaining intraday credit from the central bank, or recycling incoming payments from other system participants.[5] We find the amount of intraday liquidity that participants use by tapping their reserves or by borrowing from the central bank to be economically significant. For example, in our sample period, participants in the US Fedwire Funds Transfer System (Fedwire) collectively use an average of $630 billion of intraday liquidity every business day, with a maximum of about $1 trillion. For the Eurosystem, the daily average and maximum values are $443 billion and $800 billion, respectively. Averaged across the nine jurisdictions and over the 17-year period in our sample, participants use the equivalent of 15% of aggregate daily payment values or 2.8% of GDP[6] in order to cover their intraday liquidity needs. These numbers are large and highlight the financial stability relevance of intraday liquidity usage.

As participants often choose when to settle their payments on a given day, and as incoming payments can be used to fund outgoing ones, LVPSs may give rise to strategic effects since recycling incoming payments allows participants to economise on their own liquidity usage [Bech and Garratt (2003)]. We calculate, for each jurisdiction, a liquidity efficiency measure as in Benos et al. (2014), defined as the ratio of aggregate payment value to aggregate intraday liquidity used. This measure captures the degree to which intraday liquidity needs are met by payment recycling in a given LVPS. We show that this ratio varies substantially across systems and over time. For example, for every unit of intraday liquidity used, participants in the LVPS of the United Kingdom make on average 13 units worth of payments whereas participants in the LVPS of Denmark only make 2.5 units worth of payments.

Similarly, given that payments are recycled in an LVPS to some extent, we examine whether liquidity is provided by system participants in a manner proportional to their own payment obligations, or whether most participants rely on just a few other participants for making payments first and thereby supplying liquidity to the LVPS for the remaining participants to (re)use. This matters for financial stability because a high degree of inequality in liquidity provision could mean that the LVPS is reliant on just a few participants to function smoothly. Should these liquidity-supplying participants choose to hoard liquidity or otherwise not be able to supply it during times of stress, this could potentially affect the ability of the other participants to meet their obligations. As such, we calculate a Gini coefficient of relative liquidity provision as in Denbee et al. (2015) and show that this coefficient also varies over time and across jurisdictions.

In the rest of our analysis we seek to identify the drivers of liquidity efficiency and inequality in liquidity provision. Since intraday liquidity usage is a direct function of participant activity in an LVPS, we construct two additional variables to capture key elements of this activity, namely the timing and degree of coordination of payments. For each jurisdiction, we calculate the value-weighted average settlement time as well as a measure of payment dispersion across system participants. In panel regressions estimated across days and jurisdictions, we condition these activity variables on a number of regressors that include both time-varying factors, such as the total amount of reserves available each day and the

[5] This includes cases where participants obtain credit from one another.

[6] Relative to the combined GDP of the nine jurisdictions.

opportunity cost of holding them, as well as institutional characteristics, such as the presence of incentives to settle payments early, the central bank intraday credit regime and the various LSM design features, which pertain to the criteria and algorithms used to offset payments.[7] Our cross-system data include different combinations of LSM design characteristics, which allow us to compare and assess their impact on intraday liquidity usage.

We find that participant activity (i.e., payment timing and coordination) correlates significantly with most of these variables in a manner consistent with theoretical predictions. For example, higher levels of reserve balances are associated with earlier settlement times and reduced payment coordination, both of which are consistent with reduced participant incentives to economise on liquidity.[8] On the other hand, increases in the opportunity cost of reserves are associated with later settlement times as well as reduced payment coordination, which is consistent with liquidity hoarding, particularly in times of stress.

Although incentives to settle payments early are associated with earlier settlement times, as one might expect, we also find the incentives to be positively correlated with payment coordination. A potential explanation for this is that the incentives to pay early also increase the incentives for payment coordination as participants may not wish to deviate too much from average behaviour, as this might stigmatise them. This might be especially true if the incentives for early payment submission take the form of penalties to which deviating participants might be liable. The possibility to obtain intraday credit from the central bank at a lower collateral cost is associated with reduced payment coordination, which is consistent with weaker incentives to economise on liquidity. However, a lower collateral cost is also counter-intuitively associated with later settlement times. This is surprising, as one might expect a lower collateral cost of central bank intraday liquidity to decrease participants' incentives to delay their payments.

We also explore how participants' activity (i.e., payment timing and coordination) is related to the presence of LSMs. Overall, the presence of any LSM correlates only weakly with these variables; and while the direction of the effects is consistent with theoretical predictions, the results are not statistically significant. However, specific LSM design features are strongly correlated with the activity variables. For example, liquidity saving features of LSMs (such as the ability of LSMs to bypass the priority of payments in the queue in order to maximise offsetting benefits and the ability to offset payments on a multilateral basis) are both associated with earlier settlement times. This is consistent with theoretical predictions (e.g., Martin and McAndrews (2008)) suggesting that LSMs reduce participants' incentives to delay their outgoing payments in anticipation of incoming ones. Some of our results also suggest that system participants could potentially be conditioning their behaviour on these LSM features in a way that reduces (or even negates) their intended effect. For instance, we find that the FIFO bypass functionality, which allows LSMs to more flexibly offset payments, is associated with reduced payment coordination.

In the last part of our analysis, we specify our activity variables as regressors and our measures of liquidity efficiency and inequality in liquidity provision as the dependent variables. Given that our activity variables may not capture all aspects of LVPS participant

[7]For more details, see BIS (1997) and BIS (2005).

[8]This is also consistent with the findings of Bech et al. (2012) who look at the impact of reserve balances on settlement times in the US Fedwire system.

behaviour, we also add the above-mentioned time-varying and institutional variables as regressors. Consistent with theory, our results show that liquidity efficiency is strongly and positively correlated with the degree of payment coordination. This provides empirical support to the literature that casts LVPS interactions in a game-theoretic setting (e.g., Bech and Garratt (2003)). Our results also suggest that the amount of available liquidity as well as its opportunity cost affect intraday liquidity efficiency primarily via their effect on payment coordination.

Institutional characteristics also matter for liquidity efficiency. Incentives for early settlement help participants economise on liquidity, largely by inducing them to coordinate the timing of their payments. Our results also show that intraday liquidity usage is correlated with the collateral costs of central bank intraday credit. In regimes where intraday credit can be obtained on an uncollateralised basis, or where the cost of collateral is lower, intraday liquidity efficiency is also lower, which is driven almost entirely by the reduced coordination among participating institutions as discussed above. Finally, the presence of an LSM in an LVPS is statistically uncorrelated with our liquidity efficiency measure. This is consistent with our earlier finding that LSMs are also uncorrelated with our activity variables. Some potential explanations for this are as follows: First, a large segment of our data overlaps with periods of ample reserve balances in many jurisdictions as a result of central bank quantitative easing programs. This means that incentives to economise on liquidity have likely been lower in these jurisdictions with LVPS participants using LSMs less intensively as a result.[9] Second, different LSM features may influence participant behaviour and liquidity usage in such a way that their conflicting individual effects weaken their intended combined effects. For example, we find that payment coordination correlates negatively with the FIFO bypass functionality and positively with multilateral offsetting.

We find that inequality in liquidity provision, as measured by the Gini coefficient, is lower when (i) the opportunity cost of liquidity increases, (ii) reserve balances are higher, and (iii) institutional arrangements are in place that incentivise early payments. These results are consistent with the idea that some participants may choose to hoard liquidity when liquidity is expensive, and that an abundance of reserves alongside requirements for early payments can mitigate hoarding.

Overall, our paper is the first to study, on a cross-LVPS basis, the relationship between intraday liquidity and institutional arrangements such as the central bank's intraday credit regime, the presence of incentives for early payment submission and the design of LSMs.

The rest of the paper proceeds as follows: Section 2 reviews the literature; Section 3 describes the data; Section 4 defines and measures our variables of interest; Section 5 presents our empirical analysis and results; and Section 6 concludes.

2 Literature review

The literature on intraday liquidity is relatively scarce not least because there are no explicit intraday money markets, and payments system participants typically obtain intraday credit from central banks at low costs. This contrasts overnight liquidity, where central banks in most jurisdictions primarily rely on the overnight market to supply and

[9]Unfortunately, we do not directly observe LSM usage and as such, we cannot empirically verify this.

allocate reserves. This discrepancy, however, has motivated several theoretical studies on whether it is optimal to supply liquidity via a market mechanism or via the central bank at a predetermined, fixed price. Freeman (1999) sets up a model where the asynchronous presence of borrowers and lenders in the money market creates a need for liquidity which can be met by the central bank either via a standing facility (at a predetermined price) or by open market operations. Abstracting from moral hazard, Freeman (1999) shows that open market operations enable better risk sharing. Chapman and Martin (2013) extend this model to account for moral hazard and show that open market operations continue to yield more efficient outcomes if the central bank interacts with a select subset of participants that are themselves unaffected by moral hazard. That way, the price of liquidity reflects information available to market participants. While these arguments suggest that an explicit market for intraday liquidity might be desirable, there are also arguments in favour of the current regime: a lower cost of intraday liquidity, as typically provided by most central banks, reduces participants' incentives for delaying their payments and protects them from costly intraday overdrafts that they could have faced in an explicit intraday money market. Martin and McAndrews (2010) provide a comprehensive overview of these arguments. Our unique cross-jurisdiction data set allows us to directly test some of these theoretical predictions.

Although no explicit intraday money markets exist, several papers have looked at whether such markets nevertheless implicitly exist through differentiated prices of overnight loans with different settlement times. Studies that use data prior to the 2007-08 financial crisis generally find small but positive implied intraday rates. For example, Furfine (2001) estimates the hourly intraday unsecured rate in Fedwire to be around 0.90 bps, whereas Kraenzlin and Nellen (2010) estimate the Swiss hourly repo rate to be around 0.43 bps. Similarly, Baglioni and Monticini (2008) detect economically small intraday rates in the unsecured Italian e-MID market. However, these implied rates significantly increased during the financial crisis. Baglioni and Monticini (2010) and Jurgilas and Zikes (2014) both report more than ten-fold increases in implied unsecured intraday rates during the crisis in the Italian e-MID and Sterling markets, respectively. They argue that these rises reflect the increased opportunity costs of pledging collateral with the central bank for intraday credit. While our paper does not estimate implied intraday rates, it complements this literature by calculating the aggregate quantities of intraday liquidity deployed in each jurisdiction and by examining their determinants.

Our paper is also closely linked to the literature of payment system design, of strategic behaviour of participants within payment systems and of central bank policies regarding the provision of intraday credit. On the theoretical side, Kahn and Roberds (2009) compare the properties of pure RTGS systems with those that settle payments on a net basis (also known as deferred net settlement or DNS systems). Their paper formalises the key trade-off between RTGS and DNS systems, namely that while the latter are more liquidity-efficient, they also give rise to intraday credit exposures among system participants which may create moral hazard.

Given the prevalence of RTGS systems around the world, Bech and Garratt (2003) describe the incentives and equilibrium strategies of their participants. Their key intuition is that since incoming payments can be recycled to fund outgoing payments, this creates a rich set of possible interactions between system participants that depends on the conditions under which the central bank provides intraday liquidity. Bech and Garratt (2003) show that in a collateralised (and free of fees) credit regime, the strategies and payoffs faced by RTGS system participants are those of a "prisoner's dilemma", whereas in a priced (and uncollateralised) credit regime, they are those of a "stag hunt". The authors make the key assumption that, in a collateralised credit regime, participants always bear a collateral opportunity cost whereas, in a priced credit regime, they only do so when their payment requests are not coordinated, synchronised and therefore not offset. Under this assumption, delaying payments is always socially inefficient when credit is collateralised because the cost of collateral is sunk. On the contrary, when credit is uncollateralised and priced, delays can be efficient if they lead to liquidity savings. In all cases, Bech and Garratt (2003) consider single-stage games, meaning that in the repeated versions of the "prisoner's dilemma", one might expect efficient (cooperative) equilibria to arise.

Building on Bech and Garratt (2003), Mills and Nesmith (2008) study payments equilibria when participants strategically interact both in payment and securities settlement systems. Their analysis suggests that settlement risk may lead to late-day concentration of payments and, moreover, in the presence of settlement risk, an overdraft fee can have a greater impact on the concentration of transactions. Nellen (2019) also studies the intraday liquidity management game in the presence of credit regimes with fixed and variable costs focusing on different designs of intraday liquidity facilities provided by a central bank and associated incentives (or disincentives) for early settlement. In his model, a credit regime with variable costs leads to late settlement as it is assumed to have a positive marginal cost, in contrast to a credit regime with fixed costs which has zero marginal cost. A fixed-cost credit regime then eliminates incentives to coordinate payments if intraday liquidity is available until the end of the day. In that scenario, a strictly positive transaction fee for late settlement will incentivise early settlement. Finally, Bech and Garratt (2012) theoretically show that a wide-scale disruption (caused either by operational outages or credit events) can lead to a breakdown in coordination among RTGS system participants and thus lead to an increase in the amount of intraday liquidity used.

The empirical evidence from several jurisdictions suggests that participants coordinate their payments to some extent in order to economise on intraday liquidity. For instance, McAndrews and Rajan (2000) and Becher et al. (2008) show that in the US and UK RTGS systems,respectively, participants use incoming payments to fund outgoing ones. Becher et al. (2008) attribute the high level of payment recycling in the UK system to its small membership and throughput rules that require participants to have made certain shares of payments by value by various points in time during the day. However, payment coordination between RTGS system participants is not always a given and can break down due to some external event. Several papers have examined actual coordination failures and their impact. McAndrews and Potter (2002) document that in the days following the September 11, 2001 terrorist attacks, payment coordination between Fedwire participants dropped substantially, resulting in increased liquidity usage and triggering a short-term liquidity injection by the Fed.[10] Bech and Garratt (2012) and Benos et al. (2014) document coordination failures in

[10]For instance, McAndrews and Potter (2002) report that the ratio of daily payment values to reserve balances dropped from more than 100 before September 11 to only 18 on September 14, 2001. More recently, Badev et al. (2021) provide a comprehensive account of trends in payments volume, payments value, balances, and overdrafts, in addition to documenting changes in the behaviour of financial institutions transacting via the Fedwire Funds Service.

the wake of Lehman's default in the US and UK RTGS systems, respectively. In both cases, payments were delayed, and the evidence from the UK RTGS system further suggests that these delays were targeted at participants with perceived higher credit risk.

Finally, our paper is also related to the literature on LSMs. This literature generally examines how the presence of an LSM affects the trade-off between the cost of delaying payments and the cost of obtaining intraday liquidity to settle payments early. This typically involves a game-theoretic setup which captures the impact of an LSM on RTGS system participants' incentives. In this respect, Martin and McAndrews (2008) show that an LSM reduces participants' incentives to delay payments and this leads to payments being made earlier on average, which in turn improves liquidity efficiency and welfare. However, there can also be instances where welfare is reduced in the presence of an LSM. This can happen when several LSMs reduce the degree of strategic complementarity relative to a pure RTGS system (e.g., when an offsetting functionality reduces participants' incentives to coordinate their payments). When a high degree of payment coordination is desirable (e.g., when a few participants need to make large payments that are urgent and cannot be queued) welfare is reduced because participants are forced to obtain intraday liquidity from the central bank at a cost. Jurgilas and Martin (2013) argue that such cases do not arise in collateral-based credit regimes where it is assumed that the opportunity cost of pledging collateral with the central bank is low. Evidence of strategic complementarity is also provided by Nellen et al. (2018) who show that, as LSM queuing times in the Swiss RTGS system were reduced due to higher settlement balances, payment submissions into the queue were delayed thus offsetting the reduced queuing time. Our paper complements this literature by studying the impact of particular LSM design features on the incentives and behaviour of RTGS system participants and how these features ultimately affect intraday liquidity usage.

3 Data

The primary source of data in our paper are payment messages from the LVPSs of nine different jurisdictions: Brazil, Canada, Colombia, Denmark, the Eurosystem, Mexico, Switzerland, the United Kingdom and the United States. The payments in our data are typically large in value and are made among financial and other institutions with access to central bank reserve accounts. As such, they are made using central bank reserve balances in the local currency and, once processed, are final and irrevocable. Typical payments that are settled via LVPSs include unsecured wholesale money market loans and foreign exchange transactions. Many LVPSs also settle the cash legs of wholesale repo and securities transactions. LVPSs are also regularly used to settle margin payments to clearing houses and support other payment systems to settle net obligations. These payments can be made or received either on the system participants' own behalf or on their customers behalf. Furthermore, some LVPSs are also used to settle retail transactions.[11]

These data are available to central banks operating and/or overseeing their respective payment systems and contain information on the identities of payers and payees as well as

[11] One such system is the Swiss SIC. Nellen et al. (2018) show that retail payments in SIC help recycle settlement balances thus contributing to increased liquidity efficiency.

the transaction amount, settlement date and settlement time of the payments being made.[12] As these granular data are confidential, we aggregate them across LVPS participants and use them to construct the variables described in Section 4 on a daily frequency. Since the aggregated data do not contain participant-specific information, they are shared and put together to form a panel data set. Our data cover the period from 2006 to 2018, although data from some systems only cover sub-periods within this time range due to availability constraints. Table 1 shows the data time range available for each jurisdiction, along with the number of daily observations and the local currency of payment denomination. Our final panel consists of 21,544 observations.

Table 1: Payment data sources. This table shows the LVPSs included in our study, including their jurisdiction, number of daily observations (N), data range, and the currency in which payments are denominated.

System name	Jurisdiction	N	First date	Last date	Currency
CHAPS	United Kingdom	3148	2006-01-03	2018-06-18	GBP
CUD	Colombia	2444	2008-07-01	2018-06-29	COP
Fedwire	United States	2523	2008-06-02	2018-06-26	USD
Kronos	Denmark	3120	2006-01-03	2018-06-29	DKK
LVTS	Canada	3170	2006-01-03	2018-07-31	CAD
SIC	Switzerland	2568	2008-06-03	2018-07-30	CHF
SPEI	Mexico	1967	2008-06-02	2016-06-29	MXN
STR	Brazil	4650	2003-01-02	2020-12-31	BRL
TARGET2	Eurosystem	2604	2008-06-02	2018-07-31	EUR

To construct our variables of interest, we apply a set of filters on the raw payments data in a consistent manner across the nine systems. Given our focus on intraday liquidity, as a general rule, we only use transactions that affect a participant's liquidity position (i.e., transactions that affect the funds available across a participant's accounts to make payments at a given time). This includes all interbank payments between participants, payments that participants settle on behalf of their customers, as well as liquidity transfers to and from accounts reserved for ancillary systems, such as CLS and securities settlement systems.[13] Similarly, central bank transactions with system participants are included if they alter the participants' liquidity position, but are excluded if they are purely administrative or

[12] In the presence of an LSM, payment settlement times are different from payment submission times. The latter refers to the point in time when a payment is submitted to the LSM queue. Banks receiving instructions by customers to make payments on their behalf may also choose to settle these payments at a later time of the day. In both cases, we only use settlement times in our analysis, as only these are consistently observed across systems.

[13] An overview of selected ancillary systems in CPMI jurisdictions can be found in the CPMI Red Book: `https://www.bis.org/statistics/payment_stats/rb_qual_inf_table_ps1.pdf`

technical in nature.[14] Since central banks and ancillary systems do not behave strategically as commercial banks and similar participants may do, we do not count central banks and ancillary systems as participants and do not examine their activity.

Finally, we complement our payments data with information on the number of active participants in each LVPS, the aggregate value of central bank reserve balances and the overnight unsecured interbank borrowing rate (or alternatively the central bank policy rate) as a proxy for the opportunity cost of liquidity.

4 Variables and summary statistics

4.1 Payment system activity and intraday liquidity

We start our analysis by calculating, for each payment system, the aggregate value of payments made and the amount of intraday liquidity used. Let $t \in \{1, 2, ..., T\}$ be a time partition of the daily business hours of each payment system. Let also $x_s^{i,j}(t)$ be the value of payments sent by participant i to participant j on day s and in time interval t. Then, the total value of payments made in that system on day s is

$$P_s \equiv \sum_{i,j,t} x_s^{i,j}(t). \tag{1}$$

Given a participant's incoming and outgoing payments, the amount of intraday liquidity used by that participant is equal to the amount of liquidity that the participant needs to have in place, in the form of reserve balances or intraday credit from the central bank, in order to meet its payment obligations for the day. This is the maximum cumulative net debit position that this participant attains during the day. Using the above notation, the net debit position of participant i on day s and at time t is

$$N_s^i(t) \equiv \sum_{k=1}^{t} \sum_{i \neq j} x_s^{i,j}(k) - x_s^{j,i}(k),$$

and therefore the amount of intraday liquidity used by this participant for the day is

$$L_s^i \equiv \max_t \{N_s^i(t), 0\}.$$

The aggregate amount of intraday liquidity used in the payment system is then the sum, across system participants, of the individual amounts of own liquidity used:

$$L_s = \sum_i L_s^i. \tag{2}$$

Figure 1 plots the aggregate values of payments made and liquidity used for each system in our sample. To facilitate comparison across systems, all values are reported in USD. Daily aggregate payment values are large and measured in the trillions of USD for

[14]For example, a repayment of an overnight central bank loan is included whereas a liquidity transfer between two central bank reserve accounts held by the same participant is excluded.

the larger systems (Fedwire and TARGET2) and in the tens or hundreds of billions for the other systems. It is notable that payment values are elevated at times and in jurisdictions experiencing financial stress. This is evident, for example, in Fedwire (US), CHAPS (UK) and Kronos (Denmark) during the financial crisis of 2007-09 and in TARGET2 (Eurosystem) during the European sovereign debt crisis of 2011-13. This likely reflects increased activity in financial markets as a result of higher market volatility. For instance, some LVPSs settle the cash leg of securities transactions which tend to increase in volatile conditions, while LVPSs may also facilitate margin payments, either between market participants directly or via a clearing house, which also increase with market volatility.

The amount of intraday liquidity used in each system is also economically significant. For instance, in the US, the daily amount of intraday liquidity used in Fedwire fluctuates around \$630 billion with payment values reaching as high as \$1 trillion. The corresponding values for Eurosystem's TARGET2 are \$443 and \$800 billion respectively. Across systems and over our sample time, daily intraday liquidity usage accounts for about 2.8% of GDP.

It is also evident that the amount of liquidity used is invariably lower than the total value of payments made as system participants may use incoming payments to fund outgoing ones, thus reducing the need to draw on their reserves or borrow from the central bank. Although in all systems the amount of intraday liquidity used is highly correlated with the value of payments, as one would expect, the ratio of the two varies substantially across systems and over time. This motivates our measure of intraday liquidity efficiency.

4.2 Efficiency and inequality in intraday liquidity usage

Following Benos et al. (2014), we define intraday liquidity efficiency Q_s to be the ratio of aggregate payment values over aggregate intraday liquidity used at the system level,

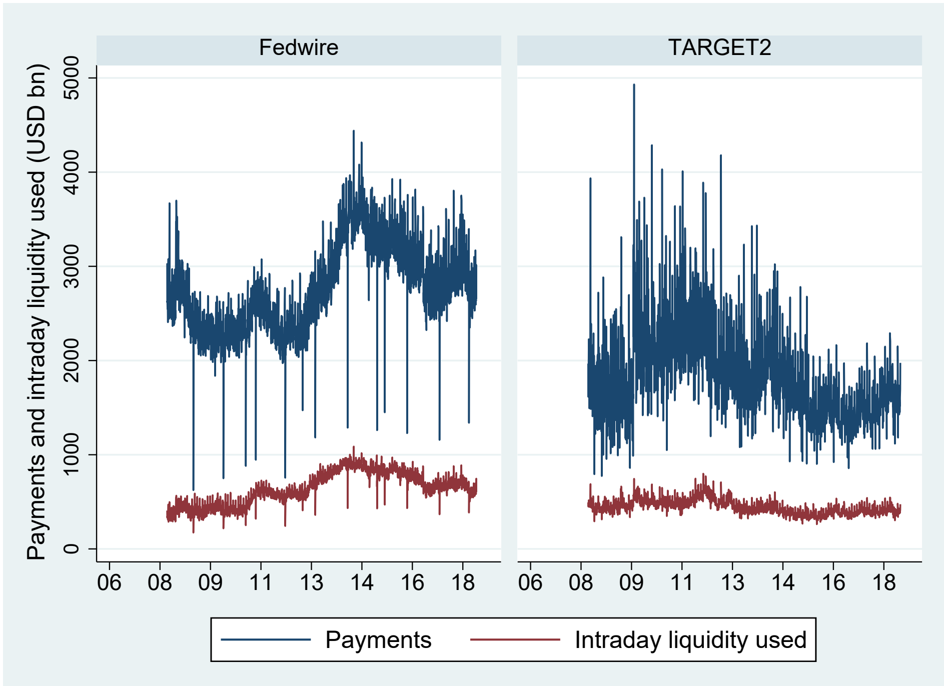
$$Q_s \equiv \frac{P_s}{L_s}. \tag{3}$$

This ratio captures the value of payments that are made for each unit of intraday liquidity used. If system participants can meet their daily payment obligations with minimal liquidity usage, the ratio takes on higher values and the system is more liquidity efficient. As mentioned earlier, liquidity efficiency will depend on the degree to which payments are recycled as well as on the extent to which payment obligations are matched and offset via an LSM.[15] Figure 2 plots daily values of this measure for each system. For most systems (CUD, Fedwire, SIC and TARGET2) liquidity efficiency takes on values between four and six, whereas CHAPS and Kronos appear to have higher and lower values, respectively, than the other systems. In all cases, there is variation over time with some systems (e.g., CHAPS and SIC) exhibiting higher variability than others. A key goal of our study is to understand why this variability arises and what makes systems more, or less, liquidity efficient.

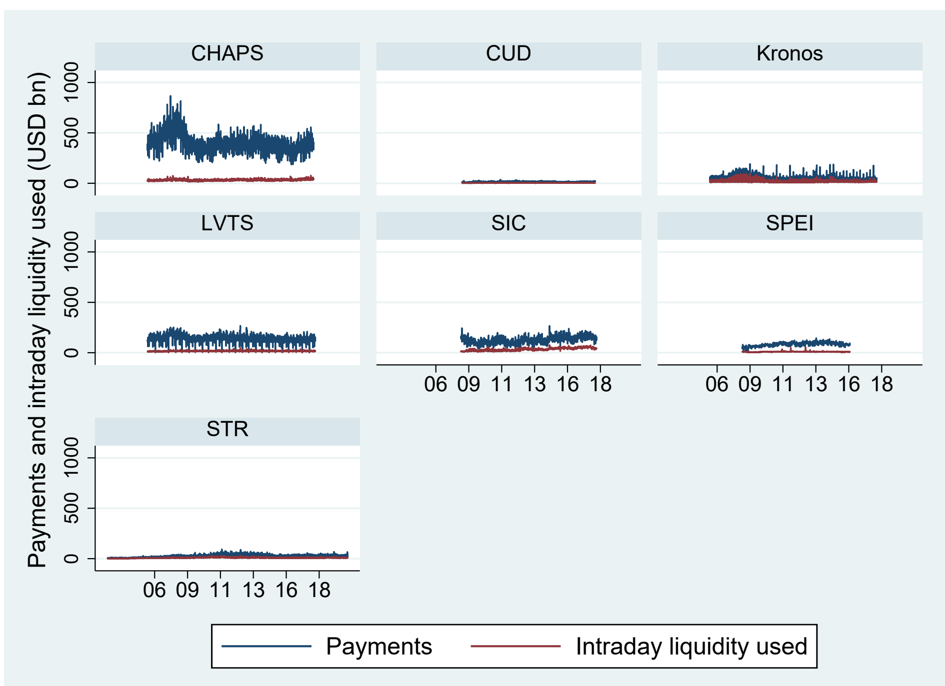
Given that payments settle on a gross basis in most systems, liquidity efficiency is ultimately determined by the extent to which payments are coordinated and thus recycled. This assumes that system participants have the option to time and coordinate their payments

[15] A system with a higher value for liquidity efficiency, as defined in this paper, does not imply that this system is overall "superior" to one with a lower value. This is because there are additional LVPS features that matter (e.g., settlement times) that are not captured by the liquidity efficiency measure.

Figure 1: Daily aggregate values (in USD billions) of payments made (P) and liquidity used (L) by payment system. The two variables are defined in equations (1) and (2) respectively.



(a) "Large" systems



(b) "Smaller" systems

and thus economise on liquidity. Whether they choose to do so should, in turn, depend on the cost of using liquidity and the ease of coordinating payments. The former will likely depend on the unit opportunity cost (and available quantity) of reserve balances, whereas the latter could depend on the presence of an LSM, which is intended to incentivise the early submission of payments.

In our empirical analysis we explore these potential determinants of cross-sectional and time variability in liquidity efficiency. Our prior is that liquidity efficiency will increase with payment coordination and that payment coordination will itself depend on participants' incentives to coordinate. For instance, we expect that an increase in reserve balances will reduce participants' incentives to coordinate their payments and thus negatively affect liquidity efficiency. Several jurisdictions in our sample (e.g., the UK, the US and the Eurosystem) engaged in quantitative easing programs that drastically increased the amount of aggregate reserves, which could have caused efficiency to trend downwards.

The opportunity cost of reserves is another potential determinant of efficiency, though it is not clear what its effect could be. On the one hand, a higher opportunity cost could incentivise system participants to coordinate their payments, leading to higher liquidity efficiency. On the other hand, it could incentivise them to hoard liquidity, which could lead to a breakdown of coordination and a drop in efficiency.

Finally, we expect that payment coordination and efficiency will likely also depend on a number of institutional features, such as incentives to submit payments early, the collateral cost of obtaining intraday credit from the central bank, the degree of tiering and the presence of an LSM with its various design features. As such, we expect that a lower collateral cost of intraday credit will dis-incentivise payment coordination (and reduce efficiency), whereas incentives for early payments will likely have the opposite effect. We are otherwise agnostic as to what is driving the sizeable time and cross-sectional variation in liquidity efficiency shown in Figure 2.

Finally, we measure how intraday liquidity usage is distributed across payment system participants and in particular whether it is proportional to the value of payments made by each participant. This is our measure of inequality in intraday liquidity usage. For this, we follow Denbee et al. (2015) and calculate the Gini coefficient over relative liquidity usage across participants in each jurisdiction. Let $P_s^i \equiv \sum_{j,t} x_s^{i,j}(t)$ be the total value of payments made by participant i on day s and let L_s^i be the participant's amount of intraday liquidity used (as defined above). Then, we define the relative liquidity usage of that participant to be

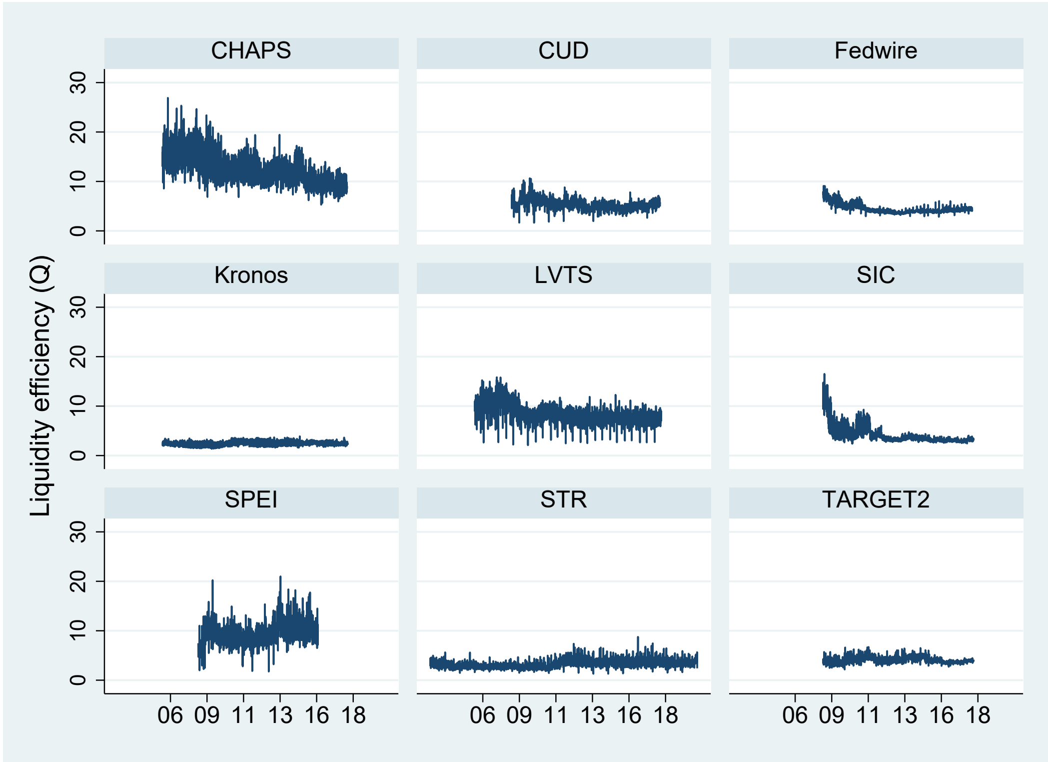
$$l_s^i \equiv \frac{L_s^i}{P_s^i}.$$

The Gini coefficient of relative liquidity usage across participants is then the volume-weighted average of the pairwise differences in relative liquidity usage,

$$G_s = \frac{1}{2M^2\mu}\left(\sum_i \sum_j m^i m^j |l_s^i - l_s^j|\right), \tag{4}$$

where m^i is the number of payments made by participant i, M is the total number of payments made by all participants, μ is the average relative liquidity usage of all payments and l^i is the relative liquidity usage of participant i.

Figure 2: Liquidity efficiency (Q) across systems. Liquidity efficiency is defined in equation (3).



The Gini coefficient takes a minimum value of zero when each participant uses the same amount of intraday liquidity relative to their payments. On the other extreme, it takes a value of one when only one participant uses intraday liquidity and all other participants recycle incoming payments and use no intraday liquidity. In Figure 3 we plot daily values of the Gini coefficient over our sample period for each system. The Gini coefficient varies substantially over time and also across systems. In our empirical analysis we explore the determinants of this variability.

4.3 Payment timing and dispersion

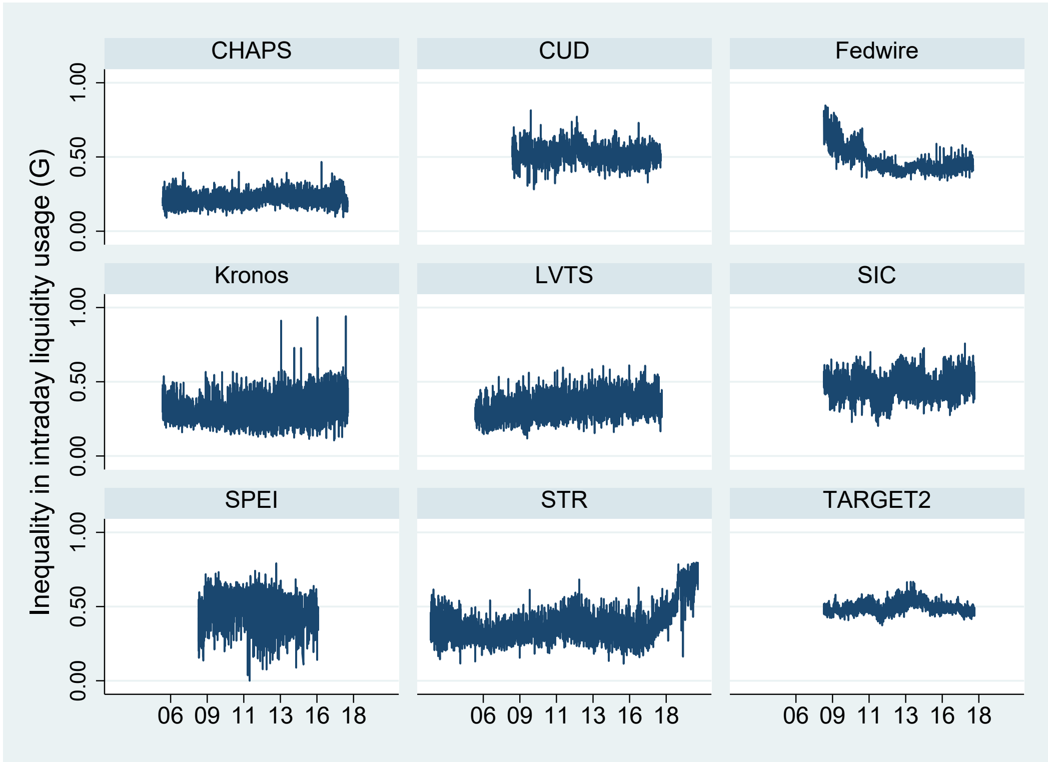
Given that intraday liquidity usage depends on the degree of payment recycling which, in turn, depends on payment timing, we construct two additional variables to capture the value-weighted average settlement time and the degree of payment coordination or, inversely, dispersion. Let $P_s(t)$ be the aggregate value of payments made on day s and in time interval t. Then the value-weighted average settlement time on that day is

$$T_s \equiv \frac{\sum_{t=1}^{T} tP_s(t)}{\sum_{t=1}^{T} P_s(t)}, \tag{5}$$

where the denominator is the total value sent through the system on day s.

To quantify the degree of payment coordination, we first calculate, for a given system, the ten deciles of daily payment timing. Payment decile $D_s(d)$ on day s is defined as

Figure 3: Inequality in intraday liquidity usage (G) across systems. Inequality is captured by the Gini coefficient of relative liquidity usage defined in equation (4).



$$D_s(d) \equiv \arg\min_k \frac{\sum_{t=1}^{k} P_s(t)}{\sum_{t=1}^{T} P_s(t)} - d \geq 0,$$

which is the earliest point in time during the day by which a fraction d of total daily payment value has been made.[16]

Our measure of payment dispersion is then defined as

$$Tdiff_s \equiv \frac{1}{2}[D_s(0.7) + D_s(0.8) - D_s(0.2) - D_s(0.3)]. \quad (6)$$

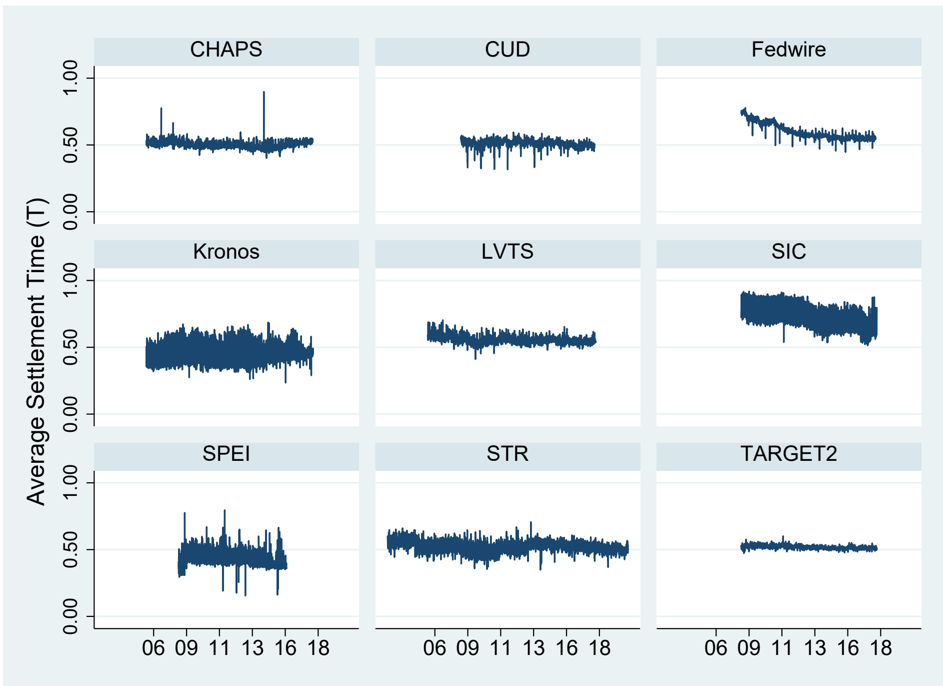
This variable can be interpreted as a proxy for the degree of payment coordination among system participants, with higher values implying less coordination and vice versa. Since it is based on payment value deciles, our dispersion measure does not depend on the time of the day that coordination of payments might take place. However, since we only observe payment settlement times and not payment submission times, this variable is a noisy proxy of the degree to which payment submission is coordinated among participants.

Both the value-weighted average settlement time and payment dispersion are plotted, for each system, in Figures 4 and 5. Average settlement time is relatively stable for most

[16] These deciles are similar to Table 1 and Chart 6 in Armantier et. al. (2008). This would be the system equivalent to Intraday throughput [C(i) of table 1 in BCBS (2013)]

systems over the longer run and centered around the middle of each system's business day.[17] However, there appears to be a downward trend for Fedwire, LVTS, SIC and SPEI. Our prior is that payment timing will mainly be influenced by the quantity and opportunity cost of reserves. The more reserves are available and/or the lower their opportunity cost, the earlier payments will be settled as participants will have less of an incentive to delay their payments to economise on liquidity. The increase in reserve balances because of quantitative easing programs in Canada, the US and Switzerland may be the reason for the downward trends in settlement time in their systems.

Figure 4: Value-weighted average settlement time (T) across systems. Value-weighted average settlement time is defined in equation (5).



Our payment dispersion measure also varies substantially across systems and over time. We hypothesise that dispersion will generally increase with the quantity of reserve balances as in those cases there will be less of a need for system participants to economise on liquidity by coordinating their payment submission times. On the other hand, it is less clear what the relationship between dispersion and the opportunity cost of reserves should be. An increase in the opportunity cost could incentivise participants to coordinate their payments more or it could incentivise them to hoard liquidity thereby increasing dispersion. Finally, while payment dispersion will depend to some degree on participants' incentives to coordinate their payments, it will also be influenced by exogenous factors beyond the control of participants (e.g., payments to and from ancillary systems often take place at predetermined times).

[17]The only exception to that is SIC, where average settlement time appears to be later in the day. This happens because SIC has much longer business hours, with the system opening in the afternoon of the previous business day.

Figure 5: Payment dispersion (*Tdiff*) across systems. Payment dispersion is defined in equation (6).

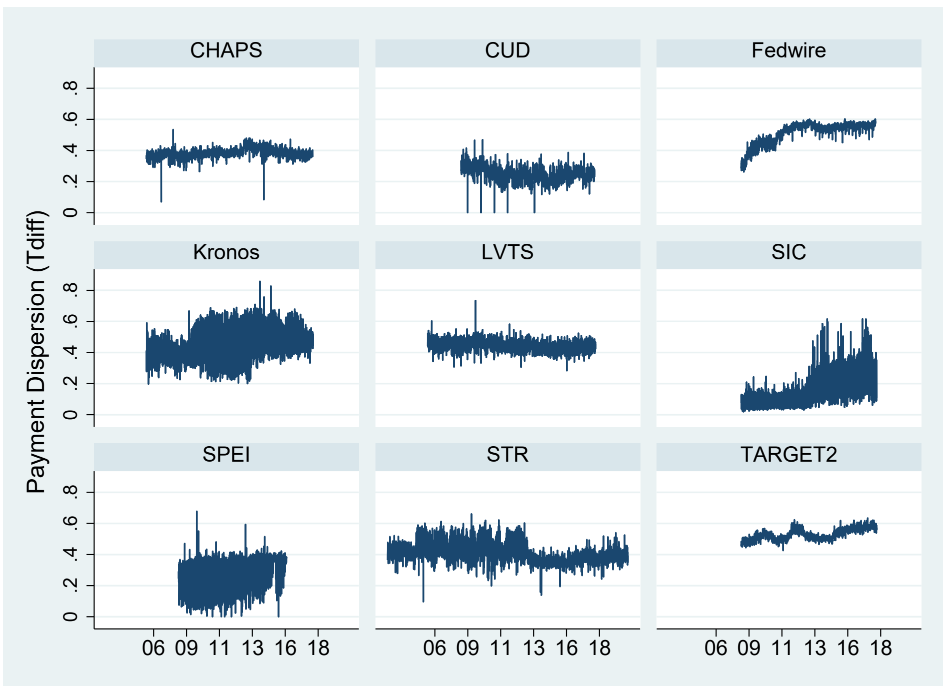


Table 2: Summary statistics. This table shows summary statistics, by payment system, for the key variables of interest. The sample properties for each system are summarised in Table 1. Variables P (in USD bn), L (in USD bn), Q, G, T and *Tdiff* are defined in equations (1)-(6). *IBOR* (in %) is either the unsecured overnight interbank rate or the central bank policy rate. *Reserves* (in $ bn) is the total size of reserve balances held with the central bank by payment system participants. The table continues on the next page.

	CHAPS (UK)				**Fedwire (US)**			
	mean	sd	min	max	mean	sd	min	max
P (USD bn)	388.33	80.45	186.45	867.14	2734.88	460.16	624.01	4440.73
L (USD bn)	31.81	6.98	11.96	77.34	629.54	172.47	173.26	1087.55
Q	12.55	2.78	5.30	26.90	4.55	0.98	2.84	9.10
G	0.22	0.04	0.09	0.47	0.48	0.09	0.34	0.85
T	0.50	0.03	0.40	0.90	0.60	0.06	0.45	0.78
Tdiff	0.38	0.03	0.07	0.53	0.51	0.07	0.26	0.60
Members	17.42	3.64	13	28	5628.18	340.23	4800	6184
IBOR(%)	1.53	1.97	0.16	6.49	0.39	0.50	0.04	2.97
Reserves (USD bn)	241.10	100.13	62.40	450.42	1718.59	690.37	1.88	2699.97
	LVTS (Canada)				**Kronos (Denmark)**			
	mean	sd	min	max	mean	sd	min	max
P (USD bn)	139.21	28.10	4.44	267.66	43.76	21.64	14.48	192.16
L (USD bn)	16.73	3.56	1.67	47.79	18.71	13.21	6.01	97.95
Q	8.46	1.77	2.09	15.84	2.52	0.40	1.35	3.90
G	0.33	0.07	0.12	0.61	0.31	0.09	0.1	0.94
T	0.55	0.03	0.41	0.70	0.43	0.08	0.23	0.69
Tdiff	0.45	0.03	0.28	0.73	0.42	0.10	0.20	0.86
Members	15.91	0.80	15	17	109.01	15.04	86	130
IBOR(%)	1.51	1.35	0.23	4.55	1.09	1.71	-1.98	6.97
Reserves (USD bn)	240.67	49.58	119.07	570.97	10.02	10.86	-20.46	61.45
	CUD (Colombia)				**TARGET2 (Eurosystem)**			
	mean	sd	min	max	mean	sd	min	max
P (USD bn)	16.36	3.43	0.22	36.63	1835.55	444.71	774.12	4931.80
L (USD bn)	3.14	0.85	0.13	12.37	442.63	74.03	261.98	799.14
Q	5.36	1.04	1.64	10.65	4.13	0.56	2.17	6.71
G	0.52	0.06	0.28	0.82	0.49	0.04	0.37	0.67
T	0.51	0.03	0.32	0.60	0.52	0.01	0.47	0.60
Tdiff	0.25	0.05	0.00	0.47	0.53	0.04	0.43	0.63
Members	132.55	8.81	12	161	969.13	99.04	747	1076
IBOR(%)	5.02	1.82	2.95	10.05	0.36	0.97	-0.37	4.60
Reserves (USD bn)	8.99	2.04	4.14	14.37	545.11	417.41	88.34	1718.05

4.4 Institutional characteristics and LSM design features

Payment systems around the world have in place different institutional arrangements that can affect intraday liquidity usage. In this paper we study two key arrangements: the presence of incentives for LVPS participants to settle their payments early and the conditions under which central banks provide intraday liquidity. The details of these are as follows:

- *Early payment incentives*: Incentives to pay early may affect payment timing and intraday liquidity usage. Incentives to settle payments earlier rather than later are

Table 2 continued

	SIC (Switzerland)				SPEI (Mexico)			
	mean	sd	min	max	mean	sd	min	max
P (USD bn)	122.65	31.05	41.48	266.26	84.79	16.99	16.14	145.18
L (USD bn)	6.60	6.88	1.12	53.74	9.51	2.65	3.12	55.36
Q	4.31	1.97	2.40	16.51	9.22	2.05	1.75	21.00
G	0.47	0.08	0.20	0.76	0.48	0.11	0.00	0.79
T	0.69	0.08	0.51	0.92	0.43	0.06	0.16	0.80
Tdiff	0.19	0.12	0.02	0.62	0.30	0.10	0.00	0.68
Members	363.92	14.44	331	387	49.84	2.26	48	53
IBOR(%)	-0.17	0.61	-1.58	3.00	4.46	1.37	3.00	8.25
Reserves (USD bn)	274.63	174.04	3.07	530.01	19.09	1.37	14.83	23.04
	STR (Brazil)				**Pooled Statistics**			
	mean	sd	min	max	mean	sd	min	max
P (USD bn)	26.26	12.30	3.03	92.78	649.92	968.71	0.22	4931.80
L (USD bn)	8.14	3.89	0.78	31.23	139.06	234.95	0.13	1087.55
Q	3.28	0.76	1.30	8.77	6.44	3.67	1.35	26.90
G	0.38	0.11	0.11	0.80	0.4	0.13	0	0.94
T	0.52	0.04	0.35	0.71	0.53	0.10	0.16	0.92
Tdiff	0.40	0.06	0.10	0.66	0.39	0.12	0.00	0.86
Members	172.69	32.07	138.00	273.00	859.89	1765.92	12	6184
IBOR(%)	11.68	4.91	1.90	26.35	3.39	4.75	-1.98	26.35
Reserves (USD bn)	15.13	6.56	4.71	41.00	374.83	591.46	-20.46	2699.97
$N = 26065$								

typically motivated by the fact that LVPS participants have an inherent incentive to delay their payments to economise on their liquidity by recycling incoming payments. They may also be motivated by operational risk considerations in that the earlier payments are released and settled during the day, the less likely they are to be affected and potentially delayed by an operational incident later in the day. These incentives can take different forms, ranging from throughput rules to late settlement fees.[18]

- *Central bank intraday credit regime*: The conditions under which central banks provide intraday liquidity to payment system participants vary across jurisdictions and are typically regarded as either collateralised or uncollateralised. In the first case, system participants need to pledge collateral with the central bank to cover the full amount of intraday liquidity that they seek to obtain. In the latter case, there are arrangements in place that allow system participants to obtain intraday liquidity from the central bank either on an uncollateralised basis or at a substantially lower collateral cost. This may include collateral pooling or more generally the ability to use collateral at low (or zero) marginal cost. For example, system participants may use unencumbered collateral pledged with the central bank for term funding to obtain intraday credit. The opportunity cost of pledging collateral will also depend on whether "double duty" is

[18]Throughput rules typically require system participants to make a certain amount of payments by various points of time during the day.

permitted.[19] If it is permitted and participants can borrow funds by pledging collateral that they have to hold, in any case, for regulatory purposes, then the marginal cost of obtaining intraday liquidity is zero.

An additional important determinant of intraday liquidity usage is the presence of LSMs and their specific design features. LSMs are queuing mechanisms that store, prioritise and offset payments. To offset payments, LSMs typically settle participants' outgoing payments if these are fully or partially offset (or matched) by incoming ones. This implies that participants' liquidity is fully or partially replenished after each payment is made, which ensures that participants do not have to use large amounts of their own liquidity, or borrow them from the central bank, to make their payments. This, in turn, should incentivise participants to submit their payments earlier on as the LSM removes the need for participants to wait for incoming payments before submitting their own. In addition, LSMs may facilitate netting of any partially or fully offsetting payments, further reducing the liquidity burden of these payments.[20]

LSMs can differ significantly across payment systems in terms of their matching frequencies, the algorithms and criteria used to facilitate matching, whether these criteria can be bypassed by system participants, etc. Furthermore, the extent to which LSMs are used by participants may also vary substantially across systems. Overall, the institutional characteristics and specific LSM design features that we include in our analysis are:

- *FIFO bypass*: This characterises the priority rules by which payments are processed in an LSM queue. Typically, payments submitted first in the queue will also be processed first on a first-in-first-out (FIFO) basis. However, some matching algorithms may apply exceptions to this priority rule to maximise liquidity efficiency. If, for example, the first payment in the queue of one system participant is similar in size to the third payment in the queue of one of its counterparties, then an LSM that can bypass the FIFO protocol would be able to match these two payments, even though it effectively skips the second payment in the counterparty's queue.

- *Multilateral offsetting*: Offsetting payments between system participants in an LSM queue can done bilaterally or multilaterally. With bilateral offsetting, payments in the queue from participant A to participant B are offset only against payments by participant B to participant A. With multilateral offsetting, payments between multiple participants can be offset if their gross outstanding payment value is larger than their net outstanding payment value. Multilateral offsetting improves liquidity efficiency as it enables netting for a wider set of payment queue configurations.

- *Priority setting*: Payments submitted to an LSM may have to wait in the queue to be settled. However, system participants may wish to expedite specific time-sensitive

[19] "Double duty" is a bank practice of using regulatory liquid asset buffers (typically measured at the end of the day) to support intraday payment system activity. In the run-up to the financial crisis of 2008-09, double duty was permitted in several jurisdictions around the world. For more details, see Ball et al. (2011).

[20] Where netting is possible, and if payments are only partially offset, the LSM ensures that a participant's payments are only released when the participant has sufficient liquidity to cover its net outstanding obligation.

payments whose delay would otherwise be costly. For this reason, some LSMs make it possible to alter the priority of payments already submitted in the queue.[21]

- *Liquidity reservations*: In some LVPSs with an LSM, system participants can also reserve liquidity to make payments outside the LSM. Typically this is liquidity earmarked for the most urgent payments.

Panel A of Table 3 lists these institutional characteristics and LSM features for which we construct dummy variables to use in our empirical analysis. Panel B of the same table shows how these characteristics vary across systems. All systems included in our sample, except Fedwire, feature LSM queuing (i.e., central queues that allow for a varying set of system features listed above). CHAPS introduced LSM queuing during our sample period, in April 2013. There is more variation in institutional characteristics and LSM features across systems, which allows us to empirically compare their effects on intraday liquidity usage.

Table 3: Institutional characteristics and LSM design features. This table describes the various institutional characteristics and LSM design features that we study and the values that the associated dummy variables take for each system. The date range for each system is shown in Table 1. In the UK, an LSM was introduced on April 22, 2013. In Switzerland's SIC, the ability to reserve liquidity was introduced on June 18, 2016.

Panel A: Dummy variable definitions

Institutional characteristics	
Incentives	Equals 1 if there are in place incentives or requirements for settling payments early
Credit	Equals 1 if the central bank can provide intraday credit on an uncollateralised basis or at a lower collateral cost (e.g., via collateral pooling)
LSM design features	
LSM	Equals 1 if there is an LSM in place
FIFO_bp	Equals 1 if the LSM allows for the FIFO protocol to be bypassed
Offsetting	Equals 1 if the LSM enables multilateral offsetting
Priority	Equals 1 if it is possible to change the priority of payments in the LSM queue
Reservations	Equals 1 if it is possible to reserve liquidity for payments outside the LSM

Panel B: Dummy variable values by jurisdiction

System name	*Jurisdiction*	*Incentives*	*Credit*	*LSM*	*FIFO_bp*	*Offsetting*	*Priority*	*Reservations*
CHAPS	United Kingdom	1	0	0/1	0/1	0/1	0/1	0/1
CUD	Colombia	1	0	1	1	1	1	0
Fedwire	United States	0	1	0	0	0	0	0
Kronos	Denmark	1	0	1	1	1	1	0
LVTS	Canada	1	1	1	0	1	0	0
SIC	Switzerland	1	0	1	0	0	1	0/1
SPEI	Mexico	0	0	1	0	1	0	0
STR	Brazil	0	0	0/1	0/1	0/1	0/1	0
TARGET2	Eurosystem	0	0	1	1	1	1	1

[21] System participants also have the option to immediately settle their payments outside the LSM queue. However, this is a common feature across all systems and as such we cannot use it to draw cross-system comparisons.

5 Empirical analysis

Our empirical analysis proceeds in two steps. First, we examine the determinants of payment timing and dispersion (or lack of coordination) as measured by the T and $Tdiff$ variables defined in equations (5) and (6), respectively. These two variables are intended to capture the most important decisions that payment system participants make: when to settle their payments and whether to coordinate with other participants in doing so. We are interested in examining whether these decisions are correlated with the opportunity cost of reserves and the aggregate amount of available liquidity, but also with the institutional characteristics of each system as summarised in Table 3. For this reason, we first estimate several models where timing and dispersion are treated as dependent variables with the opportunity cost of reserves, the available liquidity and the institutional characteristics as independent variables.

In the second step, we examine the determinants of liquidity efficiency (defined in equation 3) and inequality of liquidity provision across participants (defined in equation 4). In principle, both variables are entirely determined by the payment patterns of system participants and for this reason, our timing and dispersion metrics are now included as explanatory variables in these specifications.

A couple of caveats are however in order. First, our timing and dispersion variables are imperfect proxies of participants' payment patterns. For instance, if payments were highly coordinated at a few points in time that are relatively far apart (e.g., early and late in the business day), our dispersion metric would be high, and we would falsely interpret that as a low level of coordination. Similarly, it could be the case that for liquidity efficiency, specific timing percentiles matter as much as (if not more than) average settlement time.

Second, as mentioned earlier, we only observe settlement times rather than submission times. The former are contaminated by the random settlement processing times in systems with a queue and as such capture less accurately participants' behaviour. For these two reasons, our liquidity efficiency and inequality specifications also include as controls the same set of variables used in the first set of regressions. The goal is to allow these variables to capture any effects that our payment timing and coordination proxies might fail to properly account for.

5.1 Payment timing and coordination

In this section we examine the determinants of average settlement times (as captured by T) and the degree of payment dispersion (as captured by $Tdiff$). For this purpose, we estimate the following panel specifications across systems and over time:

$$T_{it} = a_1 + d_1 X'_{it} + u_{it}, \tag{7}$$

$$Tdiff_{it} = a_2 + b_2 T_{it} + d_2 X'_{it} + e_{it}, \tag{8}$$

where i denotes systems and t denotes days. The vector X' includes regressors that are motivated by the theoretical literature on payment timing as well as economic intuition. For instance, explanatory variables include the aggregate value of payments made (P), the total number of system participants (*Members*), innovations in the overnight interbank rate

($\Delta IBOR$), the total amount of reserves (*Reserves*) and dummies for the various institutional characteristics and LSM design features as described in Table 3. These regressors are natural candidates for our timing specifications. A higher value of outgoing payments could mean that they have to be spread more evenly during the day, affecting both their average settlement time as well as their dispersion. Similarly, the number of system participants may affect their individual incentives to settle earlier and their ability to coordinate their payments. Given that payments in LVPSs are liquidity-intensive and that participants can recycle incoming payments, the timing and dispersion of payments should also, in theory, depend on the amount of available liquidity (*Reserves*) and its opportunity cost (*IBOR*). The same is true of institutional features such as the central bank intraday credit regime and the various LSM characteristics. For instance, the presence of a mechanism that is designed to help participants economise on liquidity could reduce participants' incentives to delay or concentrate payments.

We estimate both models (7) and (8) using random effects and inference is done by clustering at the system level.[22] The results of these specifications are shown in Tables 4 and 5. With respect to average settlement time (Table 4), wider direct system participation is associated with payments being made later in the day in most specifications. This could be because incentives to delay payments might increase with the number of direct participants.[23] Alternatively, it could be because the marginal cost of liquidity and the associated incentives for delay are higher for smaller participants who tend to be present in systems with wider participation.

Increases in the opportunity cost of reserves (as captured by changes in *IBOR*) are associated with later settlement times (columns 4, 6, 12). If the opportunity cost of reserves increases, then system participants would have an incentive to delay their outgoing payments in anticipation of incoming ones. The negative relationship between available liquidity (captured by aggregate reserve balances) and payment settlement times (columns 5, 6, 12) is also consistent with this idea since aggregate reserve balances are a key instrument that central banks use to target short-term interest rates. However, the fact that reserve balances are significant after controlling for $\Delta IBOR$ suggests that there is an incremental effect not necessarily associated with the opportunity cost of liquidity. The negative relationship between reserve balances and payment timing confirms similar findings from Fedwire reported in Bech et al. (2012) and Bech and Garratt (2012). This finding is important, because several central banks in our sample engaged in quantitative easing programs after having reduced interest rates to historically low levels. These programs increased the reserve balances in their systems significantly, and our results suggest that this induced earlier payment submission.[24]

The presence of incentives to settle payments early is weakly associated with earlier

[22]We use random effects because our models feature time-invariant characteristics. Owing to the large time and small cross-sectional dimensions of our sample, in practice the random effects estimators are mostly determined by the within (time) variation of our sample and are therefore unlikely to be biased because of group unobserved, time-invariant characteristics.

[23]Given the public good nature of intraday liquidity, the incentives of system participants are similar to those faced by players in a volunteering game. In such setups, the probability that any given player volunteers decreases with the number of players. See Diekmann (1985).

[24]Early payment submission (and thereby settlement) is desirable not the least because it lowers the impact of a potential operational outage that prevents participants from sending or receiving payments in the LVPS. If a larger volume of payments has been processed before such an outage occurs, its impact will be smaller.

settlement times and only in the full specification (column 12). By contrast, the possibility to obtain intraday credit from the central bank at a lower collateral cost is associated with a later average settlement time (columns 8, 10, 12). This is contrary to what one might expect: if collateral has an opportunity cost and central bank liquidity is cheaper, system participants should be less likely to delay their payments in anticipation of incoming ones.

We also find a weakly negative association between the presence of an LSM and payment timing (columns 9, 10). This is consistent with theoretical arguments (e.g. Martin and McAndrews (2008)) that LSMs reduce participants' incentives to delay their payments by conditioning the release of outgoing payments on participants' available liquidity or incoming payments. This appears to be driven by specific LSM characteristics.

For instance, average settlement time is strongly negatively correlated with FIFO bypass and multilateral offsetting (columns 11, 12). Since these are the features that increase the potential for liquidity savings in the LSM queue, they could reduce participants' incentives to delay their outgoing payments in anticipation of incoming ones. On the other hand, priority setting in an LSM is associated with later average settlement times (columns 11, 12). This could be because the ability to prioritise specific payments in the LSM queue allows for the more urgent payments to be settled faster so that there is less of an incentive to expedite the submission of all payments in the queue.[25] Alternatively, it could be that prioritising payments within the LSM queue results in poorer offsetting matches or liquidity being blocked for high-value high-priority payments which, on average, delays settlement.[26]

Table 5 shows the results on payment dispersion. Dispersion tends to decrease with average settlement times although the effect is not statistically significant. This might arise because payments that are made later need to settle within a narrower time frame before the end of the business day. Dispersion is also negatively associated with LVPS participation (columns 11, 14). It is not immediately clear what drives this effect, but it could be purely mechanical: as the number of participants increases, the number of payments that coincide may also increase, which would tend to decrease dispersion.

Dispersion increases with the level of reserve balances (columns 5, 6, 14) and with changes in their opportunity cost ($\Delta IBOR$; columns 4, 6, 11, 14). The first effect is consistent with the idea that an abundance of liquidity reduces participants' incentives to coordinate their payments, whereas the second effect is consistent with liquidity hoarding at times of stress (i.e., when market conditions deteriorate, liquidity becomes more expensive and system participants may withhold or delay outgoing payments so payment coordination weakens and dispersion increases). The positive relation between $\Delta IBOR$ and payment timing discussed earlier seems to corroborate this.

Dispersion is also higher when it is possible to obtain intraday credit from the central bank at a lower collateral cost (columns 8, 10, 11, 13, 14), suggesting that a lower collateral cost potentially reduces participants' incentives to coordinate their payment submissions to economise on liquidity. This is consistent with the theoretical arguments in Mills and

[25]This explanation is consistent with the findings of Nellen et al. (2018) who study the relationship between submission and settlement times in SIC.

[26]A reduction in matching efficiency might result if urgent payments are larger than non-urgent ones, or if only a few system participants make them on any given day, so the chance that they are netted in the LSM queue is smaller. Unfortunately, we cannot test this specific hypothesis as we cannot distinguish between urgent and non-urgent payments in our data.

Nesmith (2008). Additionally, incentives for early payment submission are associated with lower dispersion in the full specification (column 14). Although our results showed no substantial correlation between such incentives and average settlement timing, it could be the case that these incentives induce more uniform payment patterns especially if delaying payments consistently carries a penalty. One could hypothesise that in the presence of such rules, a system participant might have an incentive to avoid being viewed as an outlier in terms of its payment patterns, which would result in lower average dispersion.

Finally, several LSM features are related to payment dispersion (columns 12-14). *FIFO bypass* is associated with higher payment dispersion. This effect is unlikely to be mechanical because, if anything, FIFO bypass increases the opportunities for simultaneous settlement of two offsetting payments which should decrease dispersion. As such, we suspect that system participants might be endogenously modifying their behaviour in the presence of this functionality. FIFO bypass could reduce participants' incentives to coordinate their payments, because even if payments are submitted to the LSM queue at different points in time, FIFO bypass will reschedule them so as to maximise any offsetting opportunities.

The same effect, in reverse, could explain the negative correlation between *priority setting* and dispersion: if priority setting overrules the offsetting algorithm and decreases offsetting efficiency, this might increase participants' incentives to coordinate their payments so as to economise on liquidity.[27]

Multilateral offsetting is also associated with reduced dispersion. This could be a mechanical effect, a behavioural effect, or both. Multilateral offsetting, by definition, enables a wider set of payments submitted by multiple participants to settle simultaneously which would reduce our dispersion measure. Alternatively, given that this functionality is more effective when more participants' payments are in the queue at any given point in time, it could ex-ante incentivise participants to coordinate their payment submission. Since we do not observe payment submission times, we cannot disentangle the effect of multilateral offsetting on the dispersion of submission times versus on the dispersion of settlement times, so we cannot see which of the two explanations drives our result.[28]

Overall, our results suggest that an LSM (or specific LSM design features) can potentially attenuate the degree of strategic complementarity that is found in pure RTGS environments. For example, a FIFO bypass functionality that reduces LVPS participants' incentives to better coordinate their payments would likely result in higher payment dispersion. Interestingly, however, our findings suggest that specific LSM features (e.g., multilateral offsetting) could also be *increasing* the degree of strategic complementarity between LVPS members by increasing the benefits of payment coordination.

5.2 Intraday liquidity efficiency

In this section we study the determinants of intraday liquidity efficiency Q. Given that RTGS systems with larger flows of payments can naturally be expected to be more liquidity intensive, we examine how liquidity efficiency, defined in equation (3), is influenced

[27] This could be the case whether LVPS participants actually use the LSM bypass functionality or not. The fact that the functionality is available could create ex-ante incentives for participants to coordinate more.

[28] See Nellen et al. (2018) for a study of the Swiss SIC payment system utilising data on both submission and settlement times.

by payment system behaviour (i.e., payment timing and dispersion), the opportunity cost and quantity of available liquidity as well as several specific LSM features.

As discussed earlier, our measure of liquidity efficiency would in principle only depend on the value, the timing and degree of coordination of payments in an LVPS. Payment system activity, in turn, would depend on (and might also influence) the price and quantity of available liquidity. However, our two variables of LVPS activity (average settlement time and dispersion), while informative, likely do not capture all aspects of LVPS activity. As such, additional variables are included as regressors in our specification for Q to account for any ultimate effects on efficiency from variables that our timing and dispersion variables fail to capture.

With this in mind, we estimate the following panel specification:

$$Q_{it} = a_3 + b_3 T_{it} + c_3 \mathit{Tdiff}_{it} + d_3 X'_{it} + v_{it}, \tag{9}$$

where i denotes systems, t denotes days and X' contains the same regressors as in model specifications (7) and (8). In addition, *Tdiff* is included as a regressor, because payment coordination allows RTGS system participants to recycle payments and thus economise on liquidity usage.

Table 6 presents the results of this specification. Indeed, a higher degree of payment dispersion is empirically associated with lower levels of liquidity efficiency (columns 2, 12, 13). This confirms the idea that in liquidity-intensive RTGS systems, payment recycling is a way for system participants to economise on liquidity. Otherwise, the timing of payments does not seem to be significantly associated with liquidity efficiency, whereas the number of system members seems to only be indirectly associated with efficiency through other variables, as its effect disappears once additional controls are included.

Changes in the opportunity cost of reserves (as captured by $\Delta IBOR$) are positively associated with efficiency only after we control for timing effects (average settlement time and dispersion). We saw earlier that increases in *IBOR* are strongly positively correlated with dispersion which negatively predicts efficiency. Thus, it is not surprising that the effect of IBOR becomes more positive in the presence of these controls. However, it is not clear how the opportunity cost of reserves would affect liquidity efficiency other than via payment coordination, which may indicate the flaws of payment dispersion as a predictor of coordination. While reserve balances are negatively correlated with efficiency in some specifications, their effect disappears once additional controls are included (columns 11-13), suggesting that reserve balances might be related with efficiency only indirectly by negatively influencing payment coordination.

The presence of incentives for early settlement is associated with higher liquidity efficiency (columns 12-14) which is likely partially driven by the negative correlation between those incentives and dispersion discussed earlier. On the other hand, the ability to obtain uncollateralised (or partially collateralised) credit seems to correlate with efficiency only via dispersion as the inclusion of our *Tdiff* variable eliminates its significance (columns 11-13).

Finally, the presence of an LSM is uncorrelated with liquidity efficiency in our sample (columns 8, 9). This could be because not all LSM features are meant to have the same effects on liquidity usage.[29] Looking, for example, at specific LSM design features, FIFO bypass is uncorrelated with efficiency, despite its strong positive correlation with our dispersion measure. On the other hand, multilateral offsetting is positively correlated with efficiency (columns 10, 11). This effect is likely driven by the negative effect of multilateral offsetting on dispersion, since the inclusion of $Tdiff$ eliminates its significance. The negative relation between priority setting and liquidity efficiency, after controlling for dispersion, could be because changing the priority of payments within the LSM queue is driven by payment urgency rather than liquidity saving considerations, resulting in poorer payment offsets. In other words, to the extent that the LSM matching algorithm releases payments in a way that minimises liquidity usage, altering payment priority may result in less liquidity-efficient matches. Finally, the ability to reserve liquidity for urgent payments could result in some liquidity being released in the payment system early in the day and subsequently being recycled to fund additional payments. This effect arises after controlling for payment dispersion and other variables, since payment reservations are themselves also positively associated with dispersion. Overall, these empirical regularities imply that the various LSM features may not have the same effects on liquidity usage.

5.3 Inequality in intraday liquidity usage

In the final part of our empirical analysis we look at the determinants of inequality in the usage (and provision) of intraday liquidity. We estimate a number of panel specifications where the dependent variable is the Gini coefficient of the relative usage of intraday liquidity G, defined in equation (4). This variable captures the extent to which some participants tap into their own available liquidity more (or less) relative to their daily payment obligations. Participants who use more of their own liquidity in relation to the value of their payments contribute to system-wide liquidity that can be subsequently recycled by other participants to meet *their* payment obligations.

Our empirical specification is:

$$G_{it} = a_4 + b_4 T_{it} + c_4 \mathit{Tdiff}_{it} + d_4 X'_{it} + u_{it}, \tag{10}$$

where i denotes systems, t denotes days and X' contains the same regressors as in the previous models. T and Tdiff are again included as regressors to gauge if payment timing and the degree of payment coordination are associated with inequality in liquidity provision.

Table 7 presents the results of these specifications. The first thing to notice is that the Gini coefficient is unrelated to our timing and dispersion variables, suggesting that it is not associated with the overall timing and degree of coordination in payments. However, it is negatively correlated with $\Delta IBOR$ (columns 4, 9, 11, 13). This suggests that when the opportunity cost of reserves increases, there is less reliance on fewer participants for liquidity and instead more participants commit their own liquidity. This is consistent with the earlier results that $\Delta IBOR$ is positively correlated with average settlement times and dispersion: if a higher opportunity cost of liquidity results in payment delays and hoarding, then one

[29] This could also be indicative of reverse causality, in the sense that systems with lower levels of liquidity efficiency are more likely to introduce an LSM. However anecdotal evidence suggests that this is a less likely explanation.

would indeed expect more participants to be forced to commit their own liquidity in order to meet their payment obligations.

The aggregate amount of reserves and the presence of incentives for early settlement are both associated with a lower Gini coefficient across models. This is likely because a higher amount of reserves reduces participants' incentives to rely on recycled liquidity provided by other participants. Additionally, the presence of incentives for early settlement limits the degree to which certain participants can recycle liquidity provided by only a few other participants, since every participant has an incentive (or obligation) to make some early payments and thereby injects liquidity in the payment system. Finally, the presence of an LSM is positively correlated with the Gini coefficient, with the effect being mainly driven by the priority setting functionality (columns 10-13). It is not immediately clear why priority setting would correlate positively with the Gini coefficient.

6 Summary and conclusions

This is the first paper to systematically study intraday liquidity usage by financial institutions in LVPSs across several jurisdictions over a long period of time. Using a unique cross-country data set, we measure intraday liquidity usage at a daily frequency, at the system level, and assess its drivers. We find that intraday liquidity usage is highly economically significant, accounting for 15% of daily aggregate payment values on average or about 2.3% of local GDP.

Consistent with the theoretical literature, we also find that intraday liquidity usage depends on the way system participants interact with one another in an LVPS. For instance, a higher degree of payment coordination is associated with higher liquidity efficiency (i.e., with a higher value of payments made for every unit of intraday liquidity used). Payment coordination in turn, depends on both policy-related variables, such as the overall supply of central bank reserve balances and system-specific institutional characteristics.

Regarding the former, we find that higher aggregate reserve balances, which are largely the result of quantitative easing programs in several jurisdictions in our sample, are associated with reduced incentives among participants to coordinate their payments and thus economise on intraday liquidity usage. On the flip side, higher reserve balances appear to induce earlier payment submission and also reduce the reliance on just a few system participants to provide liquidity to the rest. Both of these effects are desirable, as they help reduce the impact of potential operational outages in the LVPS. In general, the amounts of excess liquidity that have been injected by central banks in many jurisdictions appear to have reduced the benefit of liquidity saving and the need to manage intraday liquidity.

The most novel contribution of our paper, however, is the assessment of the effect of institutional and system-specific characteristics on intraday liquidity usage. Since these characteristics are generally time-invariant, such an analysis requires cross-country data on large-value payments, which our paper is the first to assemble. Our analysis yields several new results. First, incentives for early payment submission seem to have a stronger effect on payment coordination than actual payment submission times. Given that these incentives often take the form of penalties, it appears that they induce system participants to coordinate their submission times to avoid "standing out from the pack". Interestingly, the resulting increase in coordination renders the payment system more liquidity-efficient as it facilitates payment recycling.

Second, system participants appear to endogenise some of the LSM design features. This improves liquidity efficiency in some cases but worsens it in others. For example, multilateral offsetting is associated with increased payment coordination, which could be explained by participants coordinating their payments more in order to take full advantage of the functionality. Increased payment coordination among participants then further enhances liquidity efficiency. On the other hand, the presence of a FIFO bypass functionality, whereby the offsetting algorithm can bypass the time priority of submitted payments, is associated with reduced payment coordination. One potential explanation for that is that participants are less incentivised to coordinate their payments in the presence of FIFO bypass. This reduces liquidity efficiency.

Overall, a key insight from our paper is that, in endogenising the various payment system design features and institutional arrangements, system participants can influence the aggregate amount of intraday liquidity they use to fund their payments. We believe that understanding these endogenous dynamics is important when designing payment systems and therefore additional research in this area is warranted.

Table 4: Payment timing panel regressions. The dependent variable, T, is the value-weighted average settlement time of payments made in each system on any given day. It is defined in equation (5). P (in USD bn) is the daily total value of payments made in each system. $\Delta IBOR$ (in %) is the first difference in either the unsecured overnight interbank rate or the central bank policy rate. *Reserves* (in USD bn) is the total size of reserve balances held with the central bank by payment system participants. The *Incentives*, *Credit* and LSM characteristic dummies are defined in Table 3. The models are estimated using random effects. Robust p-values are reported in the parentheses. *, ** and *** denote significance at 10%, 5% and 1% levels, respectively.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	T	T	T	T	T	T	T	T	T	T	T	T
P	-0.0000		-0.0000			0.0000						
	(0.366)		(0.859)			(0.724)						
Members		0.0001***	0.0001***			0.0001***						-0.0000
		(0.000)	(0.000)			(0.000)						(0.499)
$\Delta IBOR$				0.0121***		0.0123***						0.0118**
				(0.009)		(0.009)						(0.019)
Reserves					-0.0001***	-0.0001***						-0.0001***
					(0.001)	(0.005)						(0.000)
Incentives							0.0192			0.0315		-0.0561*
							(0.731)			(0.472)		(0.083)
Credit								0.0636*		0.0683*		0.1933***
								(0.090)		(0.087)		(0.000)
LSM									-0.0059	-0.0059		
									(0.159)	(0.160)		
FIFO_bp											-0.1441**	-0.0759**
											(0.033)	(0.030)
Offsetting											-0.0269	-0.1451***
											(0.617)	(0.000)
Priority											0.1817***	0.1887***
											(0.000)	(0.000)
Reservations											-0.0408*	0.0157
											(0.058)	(0.620)
_cons	0.5425***	0.4299***	0.4318***	0.5282***	0.5520***	0.4955***	0.5159***	0.5146***	0.5332***	0.4970***	0.5170***	0.5760***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
R2	0.0436	0.0977	0.0980	0.0005	0.0527	0.1004	0.0014	0.0796	0.0171	0.0902	0.3394	0.6457
N	26039	26039	26039	25205	26033	25200	26039	26039	26039	26039	26039	25200

Table 5: Payment dispersion panel regressions. The dependent variable, *Tdiff*, is defined in equation (6). T, is the value-weighted average settlement time of payments made in each system on any given day. It is defined in equation (5). P (in USD bn) is the daily total value of payments made in each system. $\Delta IBOR$ (in %) is the first difference in either the unsecured overnight interbank rate or the central bank policy rate. *Reserves* (in USD bn) is the total size of reserve balances held with the central bank by payment system participants. The *Incentives*, *Credit* and LSM characteristic dummies are defined in Table 3. The models are estimated using random effects. Robust p-values are reported in the parentheses. *, ** and *** denote significance at 10%, 5% and 1% levels, respectively.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
	Tdiff	Tdiff	Tdiff	Tdiff	Tdiff	Tdiff	Tdiff	Tdiff	Tdiff	Tdiff	Tdiff	Tdiff	Tdiff	Tdiff
T	-0.3773					-0.2110					-0.5610***			-0.3549
	(0.442)					(0.685)					(0.009)			(0.274)
P		0.0000				-0.0000					0.0001***			-0.0000*
		(0.585)				(0.412)					(0.001)			(0.054)
Members			-0.0001***			-0.0000					-0.0000**			-0.0001***
			(0.000)			(0.813)					(0.016)			(0.000)
$\Delta IBOR$				0.0332***		0.0356***					0.0369***			0.0372***
				(0.000)		(0.000)					(0.001)			(0.000)
Reserves					0.0001***	0.0001***					0.0000			0.0000**
					(0.000)	(0.005)					(0.539)			(0.040)
Incentives							-0.1004			-0.0799	0.0272		-0.0246	-0.2518***
							(0.186)			(0.264)	(0.684)		(0.523)	(0.000)
Credit								0.1265**		0.1014**	0.1089***		0.1108***	0.4237***
								(0.011)		(0.034)	(0.000)		(0.000)	(0.000)
LSM									-0.0233	-0.0233	-0.0482			
									(0.360)	(0.360)	(0.235)			
FIFO_bp												0.2581***	0.2725***	0.4713***
												(0.001)	(0.000)	(0.000)
Offsetting												-0.0608	-0.1019***	-0.3855***
												(0.326)	(0.001)	(0.000)
Priority												-0.2631***	-0.2364***	-0.1472**
												(0.000)	(0.000)	(0.024)
Reservations												0.1051***	0.1051***	0.0604
												(0.000)	(0.000)	(0.133)
_cons	0.5813**	0.3719***	0.4786***	0.3824***	0.3490***	0.4834**	0.4487***	0.3537***	0.3997***	0.4305***	0.6406***	0.4347***	0.4327***	0.8505***
	(0.023)	(0.000)	(0.000)	(0.000)	(0.000)	(0.043)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
R2	0.0602	0.2647	0.1307	0.0016	0.2079	0.1661	0.1308	0.1423	0.0769	0.2462	0.5215	0.4384	0.5491	0.6429
N	26035	26035	26035	25201	26029	25196	26035	26035	26035	26035	25196	26035	26035	25196

Table 6: Liquidity efficiency panel regressions. The dependent variable, Q, is defined - in equation (3) - as the ratio of the aggregate value of payments made to the aggregate amount of intraday liquidity used. The independent variables T and *Tdiff* are defined in equations (5) and (6), respectively. $\Delta IBOR$ (in %) is the first difference in either the unsecured overnight interbank rate or the central bank policy rate. *Reserves* (in USD bn) is the total size of reserve balances held with the central bank by payment system participants. The *Incentives*, *Credit* and LSM characteristic dummies are defined in Table 3. The models are estimated using random effects. Robust p-values are reported in the parentheses. *, ** and *** denote significance at 10%, 5% and 1% levels, respectively.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
T	4.8259												2.4497
	(0.125)												(0.591)
Tdiff		-3.5611*										-12.5865***	-12.1812***
		(0.061)										(0.002)	(0.007)
Members			0.0013***						-0.0004		0.0013	0.0003	0.0004
			(0.000)						(0.721)		(0.100)	(0.678)	(0.629)
$\Delta IBOR$				-0.0383					-0.0287		0.0480	0.4552***	0.4133*
				(0.191)					(0.196)		(0.612)	(0.004)	(0.059)
Reserves					-0.0016**				-0.0017**		0.0003	0.0010	0.0012
					(0.010)				(0.029)		(0.825)	(0.397)	(0.293)
Incentives						0.1142			-1.3430		5.3491**	3.3869*	3.5877**
						(0.956)			(0.689)		(0.042)	(0.072)	(0.043)
Credit							0.5983		2.6634		-5.7255**	-2.2255	-2.8119
							(0.764)		(0.391)		(0.034)	(0.266)	(0.191)
LSM								-0.6718	-0.5579				
								(0.631)	(0.666)				
FIFO_bp										-1.6296	-5.7207	-0.4172	-0.4015
										(0.631)	(0.149)	(0.922)	(0.925)
Offsetting										3.0812*	6.5399*	3.3422	3.8002
										(0.095)	(0.099)	(0.393)	(0.328)
Priority										-0.9878	-4.6873	-7.3624*	-7.7391*
										(0.581)	(0.269)	(0.080)	(0.066)
Reservations										-2.8161***	4.5631**	5.1767***	5.1186***
										(0.000)	(0.040)	(0.005)	(0.005)
_cons	3.4915*	7.4022***	4.9260***	6.0355***	6.6009***	5.9659***	5.9090***	6.5580***	7.7179**	5.7597***	2.3485	9.4304**	7.7919
	(0.064)	(0.000)	(0.002)	(0.000)	(0.000)	(0.000)	(0.000)	(0.001)	(0.018)	(0.002)	(0.560)	(0.035)	(0.154)
R-sq	0.0036	0.0113	0.0321	0.0000	0.0114	0.0012	0.0155	0.0111	0.1352	0.0637	0.3610	0.4351	0.4363
N	26039	26035	26065	25231	26059	26065	26065	26065	25226	26065	25226	25196	25196

Table 7: Inequality in liquidity usage panel regressions. The dependent variable, G, is the Gini coefficient in relative intraday liquidity usage, defined in equation (4). The independent variables T and *Tdiff* are defined in equations (5) and (6), respectively. $\Delta IBOR$ (in %) is the first difference in either the unsecured overnight interbank rate or the central bank policy rate. *Reserves* (in USD bn) is the total size of reserve balances held with the central bank by payment system participants. The *Incentives*, *Credit* and LSM characteristic dummies are defined in Table 3. The models are estimated using random effects. Robust p-values are reported in the parentheses. *, ** and *** denote significance at 10%, 5% and 1% levels, respectively.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
	G	G	G	G	G	G	G	G	G	G	G	G	G
T	0.0113												0.1361
	(0.961)												(0.445)
Tdiff		-0.1033										-0.1735	-0.1510
		(0.487)										(0.483)	(0.518)
Members			0.0002***						0.0001		0.0000	0.0000	0.0000
			(0.000)						(0.193)		(0.474)	(0.966)	(0.888)
$\Delta IBOR$				-0.0178***					-0.0178***		-0.0192***	-0.0135	-0.0159**
				(0.002)					(0.001)		(0.000)	(0.105)	(0.036)
Reserves					-0.0001**				-0.0001**		-0.0001***	-0.0001***	-0.0001**
					(0.015)				(0.048)		(0.000)	(0.005)	(0.021)
Incentives						-0.1145***			-0.0101		-0.2110***	-0.2380**	-0.2269***
						(0.009)			(0.930)		(0.004)	(0.011)	(0.009)
Credit							-0.0054		-0.1589		0.0679	0.1162	0.0837
							(0.938)		(0.267)		(0.365)	(0.301)	(0.326)
LSM								0.0532**	0.0546***				
								(0.025)	(0.004)				
FIFO_bp										-0.0896	-0.1042	-0.0311	-0.0301
										(0.401)	(0.103)	(0.813)	(0.828)
Offsetting										0.0415	-0.0041	-0.0481	-0.0227
										(0.567)	(0.946)	(0.610)	(0.747)
Priority										0.1098**	0.2207***	0.1840**	0.1630*
										(0.017)	(0.000)	(0.010)	(0.064)
Reservations										-0.0209	-0.0859	-0.0776	-0.0808
										(0.527)	(0.217)	(0.264)	(0.257)
_cons	0.4047***	0.4501***	0.2805***	0.4109***	0.4358***	0.4870***	0.4118***	0.3697***	0.3605***	0.3660***	0.4978***	0.5952***	0.5042***
	(0.000)	(0.000)	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
R^2	0.0432	0.0241	0.0831	0.0004	0.0170	0.1851	0.0000	0.0331	0.2226	0.0570	0.4369	0.4482	0.4512
N	26021	26017	26047	25215	26041	26047	26047	26047	25210	26047	25210	25180	25180

References

Badev, A., Clark, L., Ebanks, D., Marquardt, J., Mills, D., 2021. Fedwire funds service: Payments, balances, and available liquidity. Finance and Economics Discussion Series 2021-07. Washington: Board of Governors of the Federal Reserve System .

Baglioni, A., Monticini, A., 2008. The intraday price of money: evidence from the e-mid interbank market. Journal of Money, Credit and Banking 40, 1533–1540.

Baglioni, A., Monticini, A., 2010. The intraday interest rate under a liquidity crisis: the case of august 2007. Economic Letters 107, 198–200.

Ball, A., Denbee, E., Manning, M., Wetherilt, A., 2011. Intraday liquidity: risk and regulation. Bank of England Financial Stability Paper .

Bech, M., Garratt, R., 2003. The intraday liquidity management game. Journal of Economic Theory 109, 198–219.

Bech, M., Garratt, R., 2012. Illiquidity in the interbank payment system following wide-scale disruptions. Journal of Money, Credit and Banking 44, 903–929.

Bech, M., Hobjin, B., 2007. Technology diffusion within central banking: The case of real-time gross settlement. International Journal of Central Banking 3, 147–181.

Bech, M., Martin, A., McAndrews, J., 2012. How the high level of reserves benefits the payment system. Liberty Street Economics .

Becher, C., Galbiati, M., Tudela, M., 2008. The timing and funding of cHAPS sterling payments. FRBNY Economic Policy Review , 113–133.

Benos, E., Garratt, R., Zimmerman, P., 2014. The role of counterparty risk in CHAPS following the collapse of Lehman Brothers. International Journal of Central Banking 10, 143–171.

BIS, 1997. Real-time gross settlement systems. Committee on Payment and Market Infrastructures. CPMI Paper No 22 .

BIS, 2005. New developments in large-value payment systems. Committee on Payment and Market Infrastructures. CPMI Paper No 67 .

BIS, 2008. Principles for sound liquidity risk management and supervision. Basel Committee on Banking Supervision .

BIS, 2013. Monitoring tools for intraday liquidity management. Basel Committee on Banking Supervision .

Chapman, J., Martin, A., 2013. Rediscounting under aggregate risk with moral hazard. Journal of Money Credit and Banking 45, 651–674.

Denbee, E., Garratt, R., Zimmerman, P., 2015. Identification of over and under provision of liquidity in real-time payment systems. Journal of Financial Market Infrastructures 4, 1–19.

Diekmann, A., 1985. Volunteer's dilemma. Journal of Conflict Resolution 29, 605–610.

Freeman, S., 1999. Rediscounting under aggregate risk. Journal of Monetary Economics 43, 197–216.

Furfine, C., 2001. Banks as monitors of other banks: evidence from the overnight federal funds market. Journal of Business 74, 33–57.

Jurgilas, M., Martin, A., 2013. Liquidity-saving mechanisms in collateral-based RTGS payment systems. Annals of Finance 9, 29–60.

Jurgilas, M., Zikes, F., 2014. Implicit intraday interest rate in the UK unsecured overnight money market. Journal of Financial Intermediation 23, 232–254.

Kahn, C., Roberds, W., 1998. Payment system settlement and bank incentives. The Review of Financial Studies 11, 845–870.

Kahn, C., Roberds, W., 2009. Payments settlement: Tiering in private and public systems. Journal of Money Credit and Banking 41, 855–884.

Kraenzlin, S., Nellen, T., 2010. Daytime is money. Journal of Money Credit and Banking 42, 1689–1702.

Martin, A., McAndrews, J., 2008. Liquidity-saving mechanisms. Journal of Monetary Economics 55, 554–567.

Martin, A., McAndrews, J., 2010. Should there be intraday money markets? Contemporary Economic Policy 28, 110–122.

McAndrews, J., Potter, S., 2002. Liquidity effects of the events of September 11, 2001. FRBNY Economic Policy Review , 59–79.

McAndrews, J., Rajan, S., 2000. The timing and funding of Fedwire funds transfers. FRBNY Economic Policy Review , 17–32.

Mills, D.C., Nesmith, T.D., 2008. Risk and concentration in payment and securities settlement systems. Journal of Monetary Economics 55, 542–553.

Nellen, T., 2019. Intraday liquidity facilitiesm late settlement fee and coordination. Journal of Banking and Finance 106, 124–131.

Nellen, T., Schumacher, S., Strasser, F., 2018. Settlement liquidity in SIC. forthcoming, Swiss National Bank Working Paper .

Valukas, A., 2010. Lehman Brothers Holdings Inc. Chapter 11 proceedings; Examiner's report. Jenner & Block, March .

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